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Topcolor: A dynamical approach to top-quark mass generation^{*}

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Abstract

In Topcolor theories the mass of the top quark is generated dynamically by new strong interactions coupling to the third generation fermions. This leads to potentially observable effects in flavor-changing neutral current processes involving heavy flavored mesons, as well as in the production of heavy quarks at high-energy colliders. Recent theoretical developments and potential phenomenological constraints on these models are also briefly reviewed.

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1 Introduction

The present data confirm the existence of a top quark with a mass of approximately 170 GeV and with properties consistent with the predictions of QCD [1]. Naturally, this raises the question “Why is the top quark so heavy?”. This talk deals with one approach to this problem, usually referred to as Topcolor (TopC). Our discussion will be mostly confined to one particular model; however, this will be regarded as a prototype of theories in which the large top quark mass has a dynamical origin. In such theories, the top quark participates in a new strong interaction which causes it to condense and thereby acquire a large mass, in analogy to the *constituent* mass of the light quarks in QCD. The talk consists of an outline of the simplest TopC model, a brief review of recent theoretical work and finally a discussion of phenomenology, divided into two broad categories. The first deals with flavor-changing neutral currents (FCNC’s) which arise when the third generation is treated preferentially. (Note that the b -quark, or at least its left-handed component, is necessarily dragged into the new dynamics because it is the $SU(2)_L$ partner of top.) No natural GIM mechanism can be invoked to suppress the FCNC’s in this case because the gauge interactions are no longer flavor-symmetric. The second leg of the phenomenology discussion concerns the production of heavy flavors at high-energy colliders. The consequences of TopC on some observables on the Z -peak are also commented upon.

2 A Topcolor Model

The simplest TopC model is due to Hill [2]: At scales higher than a few TeV the gauge symmetry group is extended to $SU(3)_1 \times SU(3)_2 \times U(1)_1 \times U(1)_2 \times SU(2)_L$. The groups $SU(3)_1$ and $U(1)_1$ are stronger and couple to the third generation only, while $SU(3)_2$ and $U(1)_2$ couple to the first two generations. At a scale of ~ 1 TeV the $SU(3)_1 \times SU(3)_2$ breaks down spontaneously to its diagonal $SU(3)$ subgroup, identified with QCD, giving rise to a color octet of massive gauge bosons B^A , called colorons. Their mass is determined by the scale of symmetry breaking and the $SU(3)$ couplings and is therefore of the order of 1 TeV. The colorons couple to quarks in the following way:

$$\mathcal{L}_B = g_3 B_\mu^A \left(-\tan \theta \sum_{q \neq t, b} \bar{q} \gamma^\mu \frac{\lambda^A}{2} q + \cot \theta \sum_{Q=t, b} \bar{Q} \gamma^\mu \frac{\lambda^A}{2} Q \right) \quad (1)$$

where g_3 is the QCD coupling, λ^A are the Gell-Mann matrices and θ is a small mixing angle given by $\tan \theta = h_2/h_1 \ll 1$, where h_i is the $SU(3)_i$ gauge coupling. Similarly the $U(1)_1 \times U(1)_2$ is assumed to break down to the $U(1)$ of hypercharge producing a massive

Z' boson with strong couplings to the third family quarks *and* leptons:

$$\mathcal{L}_{Z'} = g_1 Z'_\mu \left(-\tan \theta' \sum_{f \neq t, b, \tau, \nu_\tau} \bar{f} \gamma^\mu \frac{Y_f}{2} f + \cot \theta' \sum_{F = t, b, \tau, \nu_\tau} \bar{F} \gamma^\mu \frac{Y_F}{2} F \right) \quad (2)$$

Here $\tan \theta' = q_2/q_1 \ll 1$, q_i being the $U(1)_i$ gauge coupling, g_1 is the ordinary hypercharge gauge coupling and Y_f is the hypercharge of (chiral) fermion f . The coloron mediates a strong attractive interaction between t and \bar{t} as well as between b and \bar{b} , while the Z' interaction is attractive in the t channel but *repulsive* in the b channel. This is due to the different hypercharge assignments. The combined effect is then that the attractive force between t and \bar{t} can exceed a critical value for the formation of a $\langle \bar{t}t \rangle$ condensate (and hence a large dynamical top quark mass), while the more weakly coupled bottom sector remains subcritical ($\langle \bar{b}b \rangle = 0$, $m_b^{\text{dyn}} = 0$).

The $\langle \bar{t}t \rangle$ condensate spontaneously breaks the chiral symmetries associated with the top quark and gives rise to a set of three Goldstone bosons, henceforth referred to as top-pions. In contrast to the early models of top condensation [3], which attempted to identify them with the Goldstone bosons of electroweak symmetry breaking, these top-pions are new, physical degrees of freedom¹. Actually the top-pions are not exactly massless, because the top quark mass is allowed to have a small *explicit* component (~ 1 GeV) generated by the same mechanism which is responsible for the other fermion masses. Simple estimates [2] indicate that this leads to a top-pion mass of the order of 200 GeV.

In this model the issues of TopC and electroweak symmetry breaking are not addressed. Recent attempts to construct theories where these symmetries are dynamically broken by a technicolor sector are outlined in the next section.

3 Topcolor-Assisted Technicolor

In technicolor [4] the electroweak symmetry is broken by condensates $\langle \bar{T}_L T_R \rangle$ of a new kind of fermions (“technifermions”), which interact via the technicolor force. The symmetry breaking is then communicated to the ordinary quarks and leptons by interactions which couple them to technifermions at a scale of the order of 100 TeV. This mechanism [5], known as extended technicolor (ETC), generates the quark and lepton masses in this scheme. However, within the context of traditional ETC, it has been very difficult to construct a technifermion sector which, on one hand, contains sufficient custodial isospin

¹This is a consequence of the low scale Λ of new interactions, which ensures a natural hierarchy $m_t : \Lambda$, but forces the top-pion decay constant to a value too low to account for the whole of electroweak symmetry breaking.

breaking to explain the large $t - b$ mass difference, while on the other prevents this isospin breaking from diffusing into the electroweak sector and upsetting the value of the ρ parameter [6]. Now, by assigning the task of top quark mass generation to TopC, this problem may be to a considerable extent alleviated. Models which implement this idea have been constructed in Ref. 7. They feature the following basic elements:

- Technifermion condensates are responsible for the breaking of not only the electroweak symmetries but also the TopC gauge symmetries.
- In fact, some condensates break the electroweak and TopC symmetries *simultaneously*. This turns out to be crucial to the generation of mixings of the correct size between quarks of the third and first two families.
- All technifermions couple to the strong TopC gauge groups $SU(3)_1$ and $U(1)_1$ in an isospin symmetric fashion. In this way large corrections to the electroweak ρ parameter are avoided [8].
- The models are “complete” in the sense that the specified fermion and technifermion content is sufficient to cancel all gauge anomalies. The ETC gauge group, however, is not specified; the ETC interactions are simulated by “phenomenological” four-fermion terms consistent with all gauge symmetries.
- The pseudo-Goldstone bosons which typically arise in ETC models from the spontaneous breakdown of large chiral symmetry groups all acquire here a “safe” mass of the order of 250 GeV or larger.
- In a departure from the basic postulates of the simplest TopC model of the previous section, both heavy and light fermions couple to the stronger TopC $U(1)_1$ gauge group. A detailed analysis of the manifold consequences that this may have (e.g. on atomic parity violation observables, the leptonic width of the Z boson or jet production at the Tevatron, to name but a few) has not been yet carried out. Therefore, for the phenomenological discussion that follows we shall return to the “minimal” TopC scheme of the previous section.

4 Phenomenology

4.1 Low-Energy FCNC Phenomenology

In the absence of a natural GIM mechanism, FCNC processes mediated by a coloron or a Z' occur at tree level. Since these massive gauge bosons couple strongly to the third family quarks, they can have an appreciable effect on rare B -meson decays, where the Standard Model contribution arises only at loop level and is accordingly suppressed. These processes depend on the mixing angles that effect the transition from weak to mass eigenstates. There are in general four such mixing matrices, U_L, U_R, D_L, D_R , corresponding to up-type, down-type, left- or right-handed quark field rotations. In contrast to the Standard

Process	TopC BR	SM BR
$B_s^0 \rightarrow \tau^+ \tau^-$	$\sim 2 \times 10^{-5}$	$\sim 10^{-6}$
$B \rightarrow X_s \tau^+ \tau^-$	0.9×10^{-4}	3.7×10^{-7}
$B \rightarrow X_s \mu^+ \mu^-$	6.0×10^{-6}	6.3×10^{-6}
$B \rightarrow X_s \nu \bar{\nu}$	2.7×10^{-4}	4.5×10^{-5}
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$\sim 2.5 \times 10^{-10}$	$\sim 10^{-10}$

Table 1: Rare decay processes and their branching ratios in TopC and in the Standard Model.

Model, where only the combination $V \equiv U_L^\dagger D_L$ which defines the Cabibbo-Kobayashi-Maskawa (CKM) matrix is meaningful, here all four mixing matrices are well-defined entities. Their elements cannot all be deduced from the CKM matrix and are therefore unknown parameters of the theory. For the purposes of making estimates, we assume that these mixing matrices are roughly equal:

$$U_L \sim D_L \sim U_R \sim D_R \sim V^{1/2} \quad (3)$$

We will further assume typical values for the mass and couplings of the Z' : $M_{Z'} \simeq 1$ TeV, $\kappa_1 \equiv g_1^2 \cot^2 \theta' / 4\pi \approx 1$ (see eq. (2)). Note that this coupling is non-perturbative and thus the numbers obtained are at best order-of-magnitude estimates. Table 1 lists some observables that are particularly sensitive to the TopC dynamics [9] and compares the TopC and Standard Model predictions. The following additional remarks are in order:

(i) There are no published data on the processes $B_s^0 \rightarrow \tau^+ \tau^-$ and $B \rightarrow X_s \tau^+ \tau^-$, but the results on Table 1 show that an experimental effort in this direction is very desirable. (ii) In $B \rightarrow X_s \mu^+ \mu^-$ the deviation from the Standard Model prediction is rather small, because the Z' which mediates the TopC contribution couples only weakly to muons (see eq. (2)). Even so, the angular distribution of the final state leptons provides a signal quite distinct from the Standard Model [10]. This is a consequence of the fact that in TopC this decay can proceed via effective operators of a chirality structure which is forbidden in the Standard Model. Figure 1 illustrates this point in the case of the *exclusive* decay $B \rightarrow K^* \mu^+ \mu^-$. On this graph, the forward-backward asymmetry A_{FB} of the muons, defined relative to the direction of motion of the B meson in the $\mu^+ \mu^-$ c.m. frame, is plotted as a function of the dimuon invariant mass $m_{\mu\mu}$. Even for a 1 TeV Z' boson the deviation from the Standard Model is striking. It is possible that with the Main Injector, and assuming Standard Model branching ratios, CDF will be able to collect enough events to make an angular analysis of this kind possible. (iii) The decay $B \rightarrow X_s \nu \bar{\nu}$ receives a significant contribution from TopC when $\nu = \nu_\tau$. Here again there

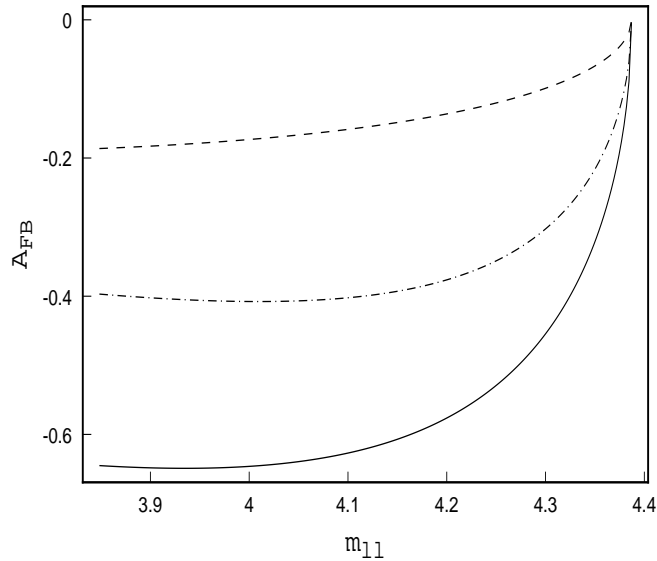


Figure 1: Forward-backward asymmetry of the muons in $B \rightarrow K^* \mu^+ \mu^-$ as a function of the dimuon invariant mass. Solid: Standard Model; dot-dash: TopC with $M_{Z'} = 1$ TeV; dashes: TopC with $M_{Z'} = 0.5$ TeV. From Ref. 10.

are no direct experimental limits on the branching ratio, but a preliminary upper bound of 3.9×10^{-4} has appeared in the literature [11]. (iv) Finally, the process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can also be of interest, given that experiments which can reach Standard Model sensitivity are planned for the near future [12]. Here, however, the new physics effects are not pronounced because only quarks of lower generations are involved.

All of the decays displayed in Table 1 are mediated by a Z' boson and are accordingly suppressed by powers of its mass. In TopC, however, FCNC processes are sometimes amplified by the effects of tightly bound states which are light compared to the scale of new interactions. It is estimated [13] that scalar bound states coupling predominantly to the b -quark may exist in the few hundred GeV mass range. Under the assumptions of eq. (3), exchange of these particles would lead to a violation of the observed mass difference in the neutral B_d meson system by approximately two orders of magnitude! Assuming the estimates are reliable, this constraint can only be evaded if at least one of the mixing factors D_L^{bd} and D_R^{bd} is suppressed. (This does not affect any of the processes in Table 1.) It is interesting to note that such a suppression of D_R^{bd} occurs naturally in the context of the Topcolor-Technicolor model of Section 3. The top-pions mediate in an analogous fashion D to \bar{D} transitions. Here the TopC prediction, under the assumption (3), is $\Delta m_D \approx 2 \times 10^{-14}$ GeV [9], still below the experimental limit of 1.3×10^{-13} GeV, but within reach in future high statistics experiments.

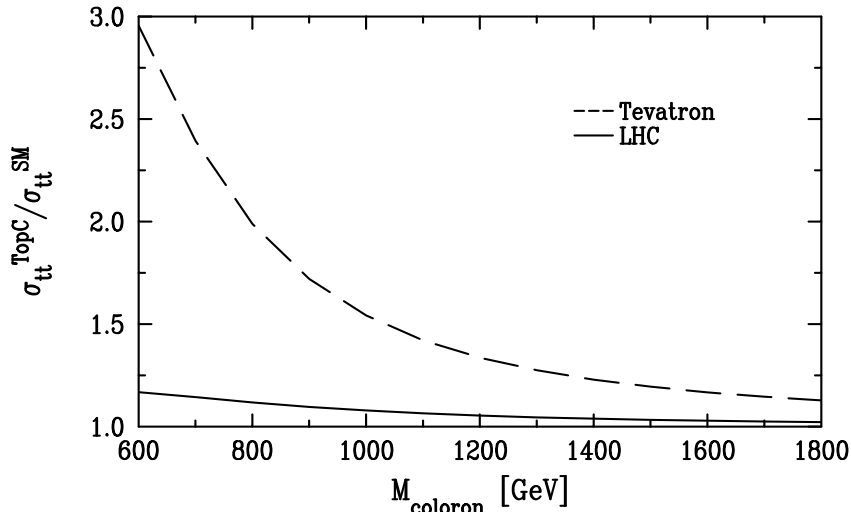


Figure 2: Comparison of top-pair production cross-section in TopC and in the Standard Model at the Tevatron and the LHC. (Inspired by Ref. 15.)

4.2 Heavy Flavor Production

In TopC pair production of third generation quarks can proceed via a coloron in the s -channel [14,15]. (Z' exchange is subdominant.) At the Tevatron, $t\bar{t}$ production requires the scattering of partons of large x and hence $q\bar{q}$ annihilation is the dominant production mechanism (with gluon fusion contributing only about 10% of the total rate). The situation is reversed at the LHC, where the center-of-mass energy is much higher and partons of lower x play the dominant role. Since the coloron can only be produced by quark-antiquark annihilation, it follows that its effects will be more significant at the Tevatron. This is illustrated in Fig. 2, where the ratio of the total $t\bar{t}$ production cross-section in TopC to the same cross-section in the Standard Model is plotted as a function of the coloron mass. Results are shown for both the Tevatron and the LHC. A top quark mass of 175 GeV is assumed. As the error bars on the top quark mass and production cross-section from the CDF and D0 shrink, limits on the coloron mass will arise.

The TopC gauge bosons will also cause distortions to the shape of various distributions [14]. The effect will be particularly noticeable in the $t\bar{t}$ invariant mass distribution, where the coloron will appear as a broad shoulder over the continuum. The same remarks apply to $b\bar{b}$ production. An experimental search in this channel has set a first bound of $M_B \gtrsim 370$ GeV on the coloron of a slightly modified version of TopC [16].

The CDF collaboration has recently reported an excess in the inclusive jet cross-section at high p_T relative to Standard Model expectations [17]. The conventional TopC model of Section 2 can only lead to an excess of b -jets, because the new heavy gauge bosons

decay predominantly to third generation quarks. However, the observed effect could be attributed to the massive gauge bosons of alternative TopC models [18], in which some or all of the light quarks participate in the new strong interactions as well. Detailed fits of TopC models to the CDF data have not, however, been performed so far.

Finally, it should be mentioned that the new TopC interactions may induce potentially large corrections to Z -pole observables. Lepton universality, for instance, is violated because the Z' , which mixes with the Z , couples more strongly to the τ lepton. Hence a lower bound of approximately 1 TeV on the Z' mass can be derived if $\kappa_1 = 1$. This bound scales roughly with the square-root of κ_1 . Regarding $R_b \equiv \Gamma(Z \rightarrow b\bar{b})/\Gamma(Z \rightarrow \text{hadrons})$, the positive coloron vertex correction [15] may be offset by negative contributions due to top-pions [19]. The issue is still under study.

In this talk, I reviewed recent developments in theories in which the large top quark mass is tied to new strong dynamics of the third generation. The aim was more to explore the sensitivity of various physical processes to this kind of new physics than to promote any particular realization of it. It was shown that this new dynamics can manifest itself in FCNC processes, such as $B - \bar{B}$ or $D - \bar{D}$ mixing and leptonic and semileptonic B meson decays, as well as in the production of heavy flavors at high-energy colliders.

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